

Final Report
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Task Objectives

The objectives of the contract were:

- Develop and test fluorescence-based algorithms from MODIS for studies of ocean productivity
- Validate these algorithms using ship and laboratory-based measurements
- Develop and expand browser-based information system for in situ bio-optical data and MODIS imagery.
- Develop software for MODIS Direct Broadcast facility for cruise support and other oceanographic studies

Work Accomplished

MODIS Fluorescence Algorithms

Two basic algorithms were developed using MODIS measurements (MOD20). The first, Fluorescence Line Height (FLH), is based on the unique capabilities of MODIS (a result of the sensor's narrow bands and high signal to noise ratio (SNR) design) to detect the small fluorescence signal produced by chlorophyll *a*. The second algorithm, Chlorophyll Fluorescence Efficiency (CFE), is a proxy for the chlorophyll fluorescence quantum yield, i.e. the amount of chlorophyll fluorescence emitted per unit photon captured by phytoplankton. CFE depends on the Absorbed Radiation by Phytoplankton (ARP) product developed by Ken Carder (MOD22). A third product, Fluorescence Baseline, is used in the calculation of FLH and has no particular meaning. A revised Algorithm Theoretical Basis Document (ATBD) and an updated Data Quality Summary are available on the MODIS Oceans team web site.

The algorithms were implemented as part of the MODIS Oceans processing system developed at the University of Miami and delivered to MODAPS. Early sensitivity analyses of these algorithms based on the specified requirements of the sensor were performed by our group (Letelier & Abbott, 1997) and suggested that MODIS could detect chl *a* concentrations changes in the range of 0.25 mg m⁻³.

The fundamental structure of the algorithms has not changed other than the sensor-specific information for MODIS/Terra and MODIS/Aqua. However, alternative algorithms for the estimation of ARP using a modified approach based on the work of John Cullen and Yannick Huot, and their effect on CFE derived fields have been tested using MODIS data collected by the Direct Broadcast Station at Oregon State University.

Validation of MODIS Fluorescence Algorithms

1) FLH

Frank Hoge collected AOL natural fluorescence data and compared them with a MODIS image of the Gulf Stream (Hoge et al., 2003). The first figure shows the MODIS image and the AOL flight line (Fig. 1). Note that the estimates of FLH from MODIS and AOL are in excellent agreement and that the retrieval is not affected by Colored Dissolved Organic Matter (CDOM).

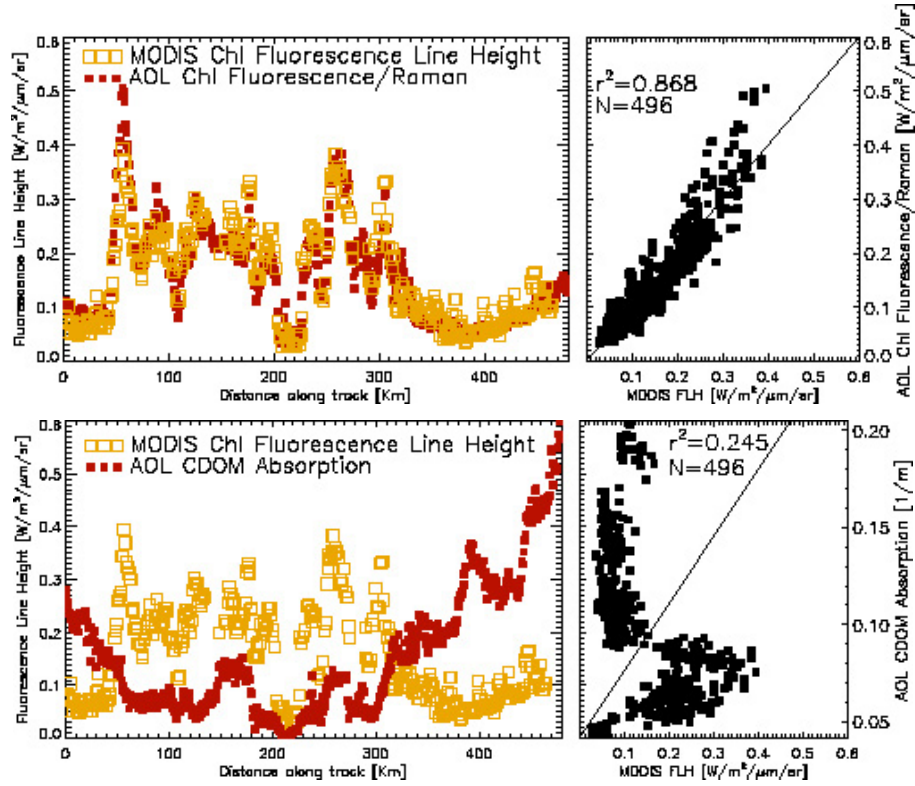


Fig. 1: Comparison between MODIS-Terra derived chlorophyll FLH and NASA Airborne Oceanographic Lidar chlorophyll fluorescence (TOP) and Colored Dissolved Organic Matter (BOTTOM) off Chesapeake Bay (from Hoge et al. 2003).

In addition, between 2000 and 2003 we deployed optical drifters off the Oregon coast and Hawai'i and tethered spectral radiometers buoys (METOCEAN Data Systems and Satlantic Inc, respectively) that measure downwelling and upwelling radiances at wavebands that allow the in situ derivation of FLH. Comparison between in situ and MODIS Terra derived FLH for the upwelling region of the Oregon Coast (Fig. 2) suggests good agreement between both estimates.

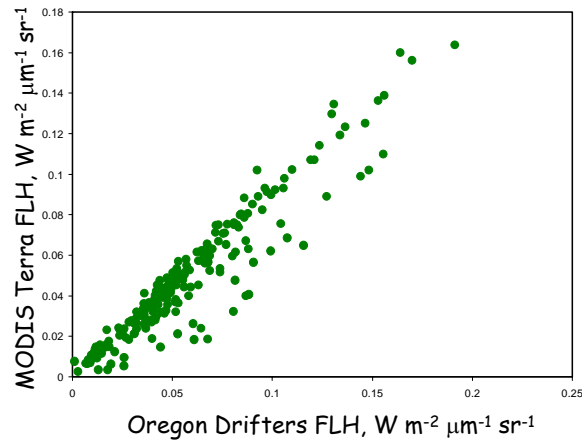


Fig. 2: Matchup of MODIS-Terra and optical drifter chlorophyll FLH off the Oregon Coast. Drifter data corresponds to averaged observations collected between 10 AM and 4 PM the date the MODIS observation was made.

These deployments were also designed to characterize the in situ dynamics of FLH as a function of solar

irradiance and chlorophyll concentration in distinct oceanic regions. As expected, FLH increased as a function of both solar irradiance and sea surface chlorophyll concentration. However, both increases are non-linear (Figs. 3 and 4). While the observed decrease in FLH per unit PAR as a function of solar irradiance (Fig. 3) can be attributed to non-photochemical quenching and photodamage of light reaction centers, the decrease in FLH per unit chlorophyll as sea surface chlorophyll increases can be attributed to the re-absorption of fluorescence by chlorophyll (Fig. 4).

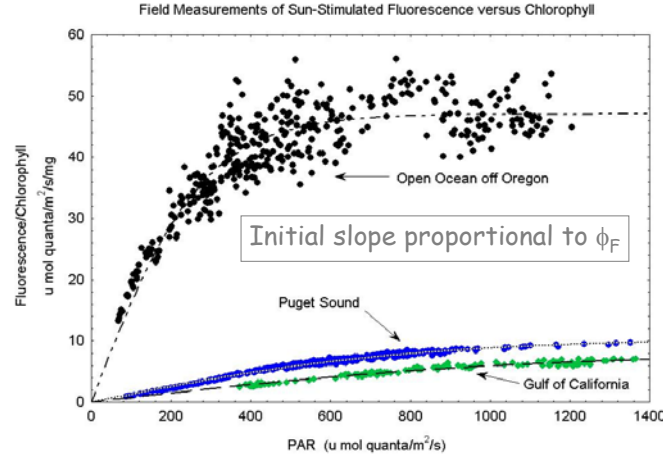


Fig. 3: Fluorescence per unit chlorophyll a as a function of surface PAR derived from data collected off the Oregon Coast using a tethered spectroradiometer buoy (TSRB, Satlantic Inc.).

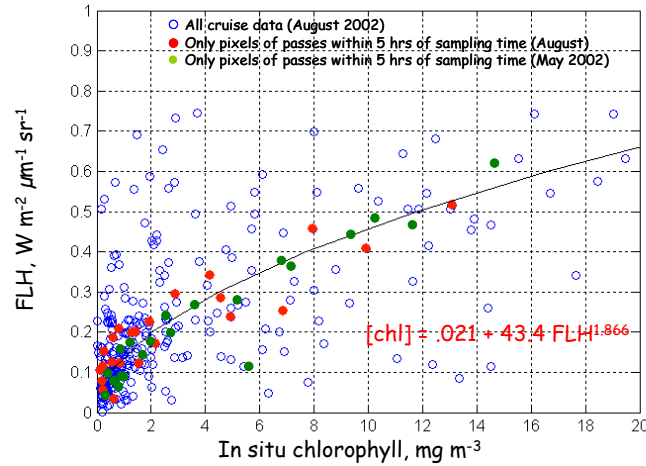


Fig. 4: Matchup of MODIS-Terra FLH and in situ chlorophyll measurements off the Oregon Coast. Only pixels of passes within 5 hours of sampling collection time during the August 2002 cruise were used to derived an empirical relation between MODIS FLH and sea surface chl a.

Both sea surface chlorophyll concentration derived from MODIS FLH in case II waters using a purely non-linear empirical chlorophyll/ FLH relationship or applying a semi-empirical algorithm that include fluorescence re-absorption by chlorophyll (see Huot and Cullen, 2002) provide close agreement with in-situ observations collected off the Oregon Coast during August 2002 (Figs. 5a, c, and d). In this particular example the MODIS chlorophyll a₂ algorithm underestimates significantly chlorophyll concentrations (Fig. 5b). This underestimation may have been caused by an extensive smoke plume from forest fires that drifted over the sampling regions. Comparison of the stability of FLH signal retrieved from MODIS-Terra during this smoke plume event suggests that FLH retrieval is not significantly affected by atmospheric correction. Because the retrieval of both nLw667 and nLw678 are affected similarly by the atmospheric correction model used, any deviation caused by the correction is cancel

when the FLH baseline is subtracted from nLw678 to derive FLH. Both, the relative insensitivity of the FLH signal to the presence of CDOM and to the atmospheric aerosol model used strongly suggest that FLH may be used efficiently in the retrieval of sea surface chlorophyll concentration in coastal waters.

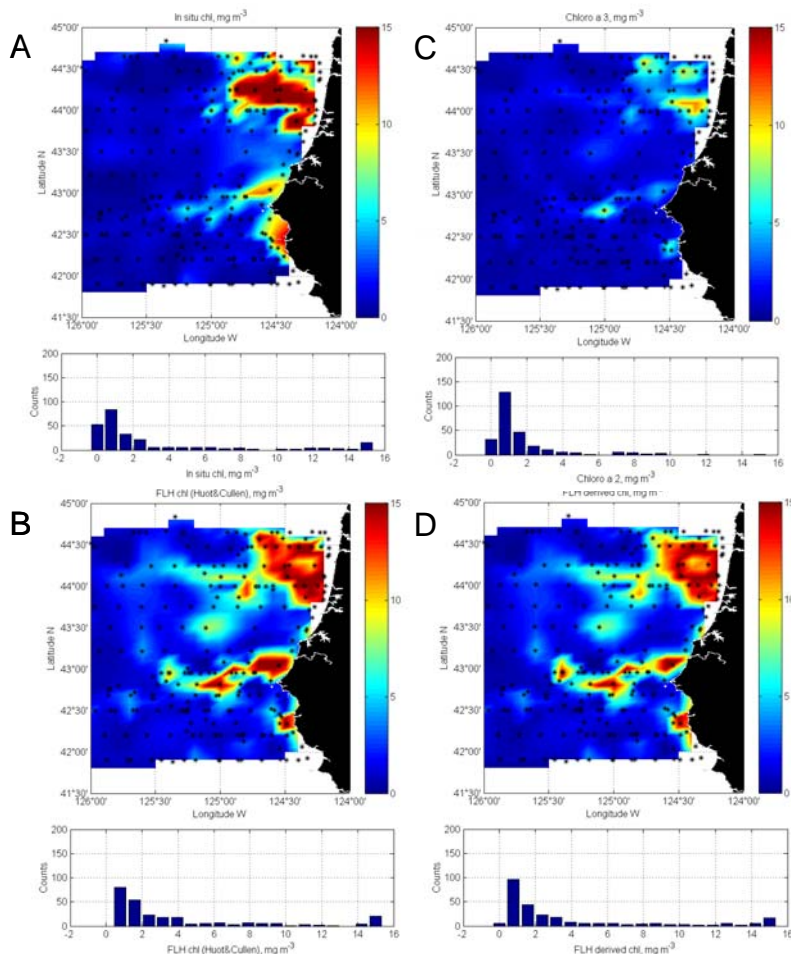


Fig. 5: Comparison between the spatial distribution of in situ chlorophyll a collected at 5 m depth off Oregon during August 2002 (A), of chlorophyll a derived from MODIS chl_a2 (B), and of chlorophyll a derived from MODIS FLH using an empirical relationship between FLH and chl a (C) or a semi-analytical model from (Huot and Cullen, 2002) assuming a constant fluorescence quantum yield ($\Phi_f = 0.006$) (D).

2) CFE

Because the validation of the CFE product depends on ARP it is not possible to declare CFE as a valid product until Ken Carder declares his product to be valid. Nevertheless, we performed analysis of time series of MODIS fluorescence products from the Oregon coast, Hawai'i, and the Southern Ocean to ensure that the products are consistent with reported historical values and algal physiology.

Given the low water-leaving radiance signal in the red wavelengths, traditional validation approaches, such as those derived from MOBY data for the blue and green wavelengths, are not sufficient. Long-term consistency in the data record and "reasonableness" of the signal levels for a particular ocean regime, are the only ways to validate this fluorescence product at the present time.

Although the distribution of CFE values in different oceanic regions is consistent with our understanding of algal physiology and with in situ values reported in the literature, a close analysis of the spatial distribution of MODIS ARP values and the derived CFE (Fig. 6), when compared to chlorophyll a distribution and ARP derived using alternative approaches (Huot and Cullen, 2002) suggests that more work is needed in both ARP and CFE before these products are validated.

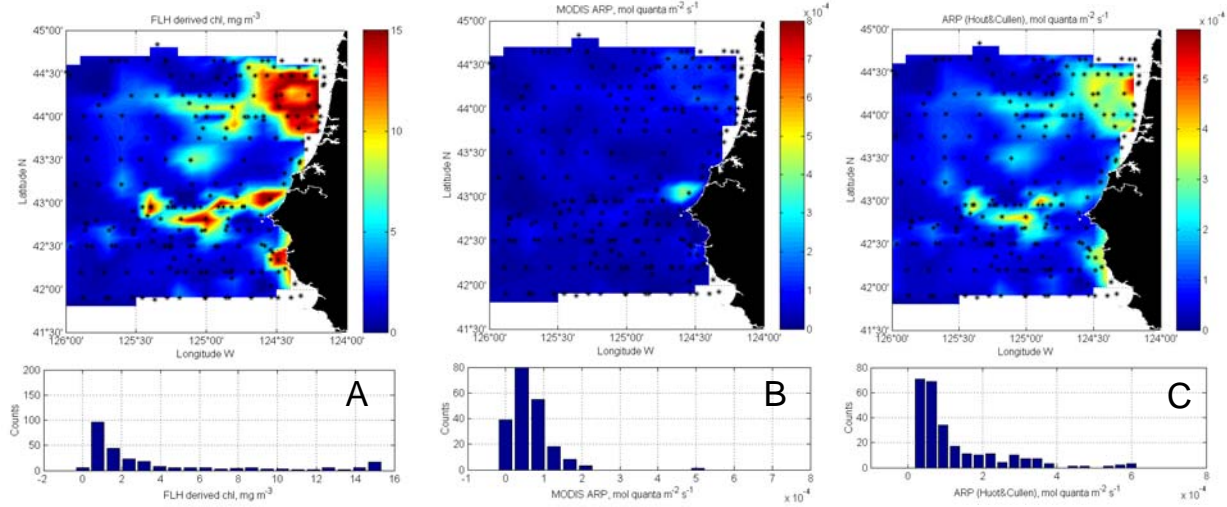


Fig. 6: Comparison of in situ (A) chlorophyll a distribution and MODIS-Terra derived ARP using MODIS ARP algorithm (B) and an algorithm based on Huot and Cullen (2002) (C)

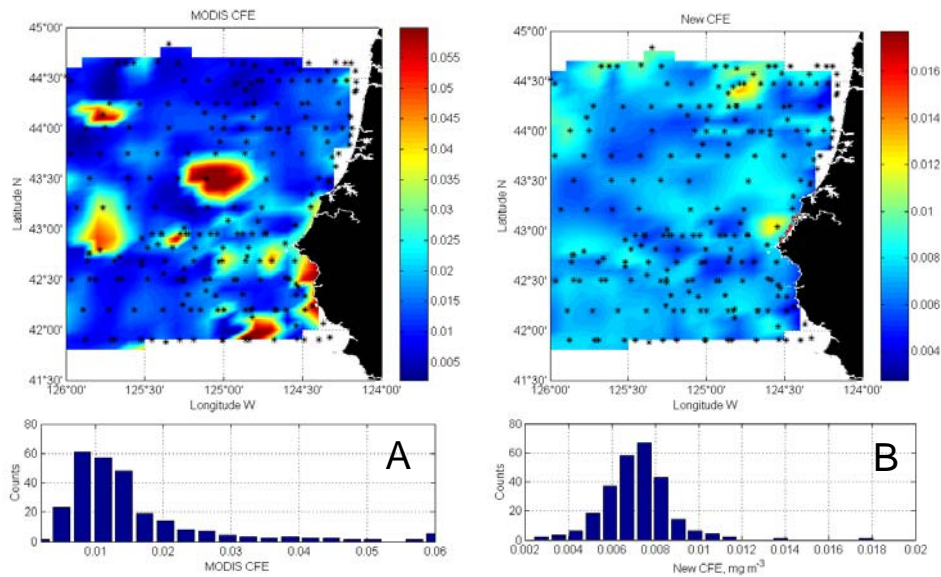


Fig. 7: CFE derived using MODIS ARP algorithm (A) and an ARP algorithm derived from Huot and Cullen (2002) (B)

At present it is not possible to determine which ARP algorithm is the appropriate one. A series of in situ phytoplankton absorption data collected during this and other cruises is being used to address this issue.

However, even if we are able to retrieve accurate CFE values, their physiological interpretation will be dependent on our understanding of factors affecting the energy distribution within the photosystem of phytoplankton assemblages. For this reason we developed a series of laboratory and field experiments aimed at better characterizing the physiological and ecological bases of CFE variability.

Chemostat Experiments

Samuel Laney and Amanda Ashe addressed the validation of the physiological parameters derived from the field measurements obtained by the FRRF with a series of laboratory experiments (Laney et al. 2001). These experiments included comparison of natural fluorescence over a full range of physiological measurements with photosynthetic parameters derived from Fast repetition Rate (FRR) and Pulse Modulated Amplitude (PAM) fluorometry. We also compared the FRRF data with oxygen evolution curves

and photosynthesis versus irradiance (P vs. E) curves obtained from the natural fluorescence chemostat.

These chemostat studies, using *Thalassiosira weissflogii*, indicate that changes in Chlorophyll Fluorescence Efficiency (CFE) are inversely related to the maximum quantum yield of photosynthesis (Fig. 8). However, both CFE and the maximum quantum yield of photosynthesis appear to be independent of growth rate under balance growth conditions. These results suggest that the variability in CFE may be used as an indicator of how far a given phytoplankton assemblage is removed from equilibrium, validating the interpretation of field observations in Antarctic waters by Letelier et al. (1996) and in the Bering sea (Schallenberg et al., 2002). However, it may be difficult to derive absolute growth rates from this parameter alone.

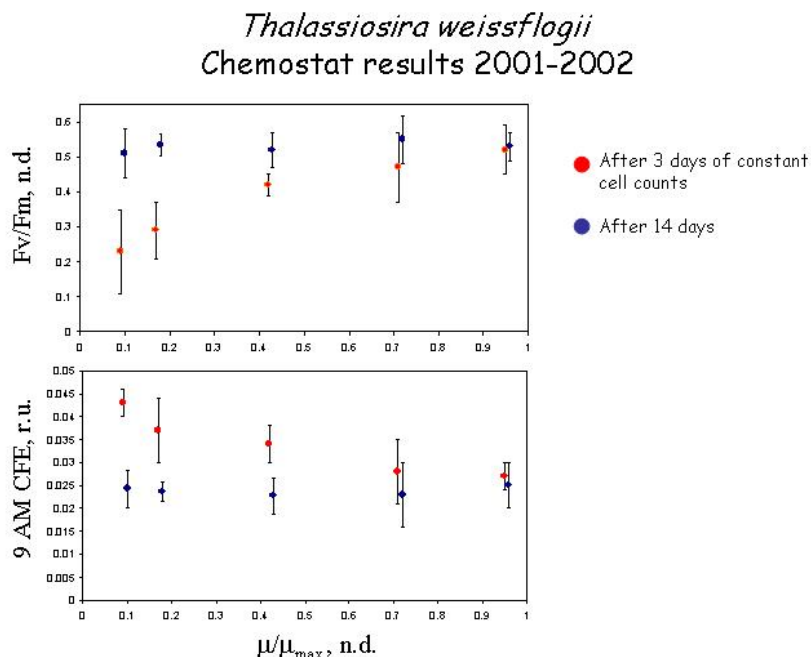


Fig. 8: Relationship between maximum photosynthetic quantum yield (Top panel) and Chlorophyll Fluorescence Efficiency (CFE, Bottom panel) as a function of relative growth rate under unbalanced (red) and balanced (blue) growth conditions.

Because the chlorophyll fluorescence quantum yield varies as a function of PAR (Fig. 3), the analysis of the dynamics of CFE over the diel solar cycle may provide information from which photochemical and non-photochemical quenching of the fluorescence signal can be extracted. This information is needed if a meaningful relationship between fluorescence quantum yield and the maximum photosynthetic quantum yield is to be derived. Both, laboratory (Fig. 9) and field observations indicate that CFE reaches its maximum value during early morning and then decreases as a result of non-photochemical quenching. However, under limiting nitrate conditions non-photochemical quenching occurs at lower light levels. Although it is not possible to determine these fluorescence dynamics using only a few measurements per day (as it is the case with MODIS Terra and Aqua in mid and low latitudes), these results indicate that repeated remote sensing observations of phytoplankton fluorescence over the diel solar cycle, such as those that could be obtained from a geostationary coastal ocean color sensor) may provide a wealth of information regarding the spatial and temporal distribution of the physiological state of phytoplankton assemblages.

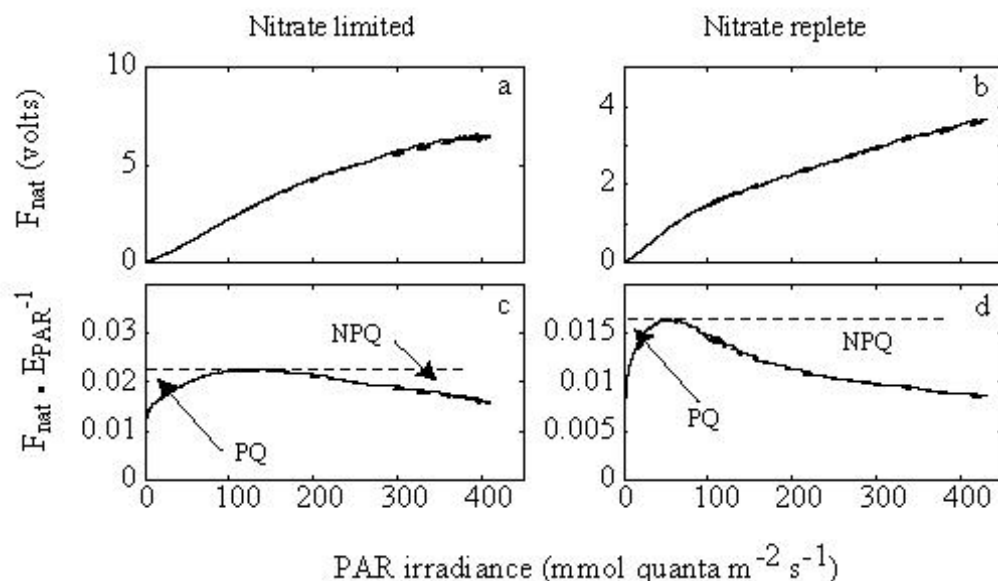


Fig. 9: Chlorophyll natural fluorescence as a function of PAR for *Thalassiosira weissflogii* under nitrate limited (A and C) and nitrate replete (B and D) conditions.

Direct Broadcast

Near real-time MODIS data (AQUA and TERRA) of the western U.S. and central North Pacific Ocean are provided by the Oregon State University direct broadcast facility. A four-meter satellite dish system in Corvallis, Oregon has collected, processed, and reprocessed MODIS-Terra data since February 2001 and MODIS-Aqua since 2002, using the latest available algorithms from Miami and MCST. MODIS data collected in Hawaii are also processed in near real-time by Oregon State University, in collaboration with the University of Hawaii. Automated pass collection, data processing, website updates, and data subscriptions provide swift access of calibrated radiances (Level 1b) and ocean products (Level 2 and daily Level 3) to the public (<http://picasso.coas.oregonstate.edu/ORSOO/MODIS/DB/>). These direct broadcast data have proved invaluable to numerous research efforts, including the real-time monitoring of pollution off the coast of Southern California, and as support during research cruises. In the latter case, real-time knowledge of the position of oceanic features allows researchers at sea to make informed decisions regarding their sampling locations and strategy. Real-time science data are essential for monitoring transient events on land and at sea.

In addition, two MODIS workshops were organized in Oregon. The first one for US EOS-DB users was held in early September 2001 on the slopes of Mt. Hood, Oregon. A CD containing all of the presentations has been produced and copies can be requested from Jasmine Nahorniak (jasmine@coas.oregonstate.edu). The second workshop, held at Oregon State University on September 2003 was aimed at the international scientific community at large interested in using MODIS derived ocean products. Presentations, Tutorials and participant feedback from this workshop are available on line at <http://picasso.coas.oregonstate.edu/ORSOO/MODIS/workshop/>.

EOSDIS Plans

We continue the development of a COM+ event model at the database end. The system allows monitoring of events and provides interested clients with notifications. Furthermore, it monitors the satellite data being received, as it enters the database. When it detects certain variations in the data, a message can be sent to a remote client. These variations could be simple changes in drifter locations or far more complex patterns involving multiple parameters. Data from the ESO DB system are being loaded automatically into the data base.

Problems and Solutions

The MODIS software is now available for the Direct Broadcast site. This is a significant improvement! We can now generate all of the MODIS Oceans products using the latest versions of the algorithms. The support from MCST and the University of Miami is greatly appreciated!

The quality of the latest MODIS products is superb. The only limitation is sufficient processing capacity within EOSDIS to generate all of the MODIS data using a consistent set of algorithms.

The MODIS fluorescence data products for MODIS-Terra have been validated. However, further work on MODIS ARP is needed before the CFE product can be considered valid. Also, MODIS-Aqua fluorescence products need to be validated. This cannot be achieved until MODIS Fluorescence bands are processed under the new NASA MODIS ocean color processing scheme.

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